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Development of a Demountable, Re-usable Transducer for the Measurement of Strain in Steel Structures

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ABSTRACT

This report describes the design and testing of a demountable strain gauge used for the measurement of low dynamic strains on steel structures. The report presents simple graphs of the gauge output compared to that of electrical resistance strain gauges. Expected errors are shown, and recommendations are offered for proper use as a demountable, reusable transducer for the measurement of strain in steel structures.

ACKNOWLEDGEMENTS

The assistance of L. Pena, Research Laboratory Technician, in testing of the transducer and recording data during transducer development, is acknowledged. The frequency response testing by Mr. J. Tiessinga P. Eng., was of great value, and his contribution to this work is also recognized.

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1/ INTRODUCTION

A requirement was identified early in 1980 for a demountable strain gauge to be used for the measurement of very low dynamic strains on a steel and concrete bridge crossing the Shawanaga River on Highway 69, north of Parry Sound, Ontario. The measured strains were to be used to indicate the weights of vehicles passing over the bridge.

Since low values of strain were to be measured, a signal approximately five times greater than that which could be expected from a single active electrical resistance strain gauge was desirable.

A transducer, based on a design principle by Dr. F. Moses of Case Western Reserve University, was developed in the Research Laboratory of the Ontario Ministry of Transportation and Communications (MTC). After confirmation of the transducer's performance characteristics, a number of the instruments were manufactured and used successfully in the Shawanaga River Bridge tests during the summers of 1980 and 1981.

This report presents summaries of the design principles of the demountable transducer and of the development testing conducted to measure its performance.

2/ CONCLUSIONS

2.1/

The transducer designed for use at Shawanaga, and to be used for the measurement of strains on any large steel structure, satisfied the following requirements:

- resolution of ± 1 με;
- minimal zero drift due to temperature;
- linear output;
- repeatable in the range of interest;
- easily demountable and re-usable;
- gain of approximately x 5;
- calibration maintained on remounting;
- excitation 3 to 5 V dc;
- output of approximately 2.5 μV/V/με; and
- frequency response of 0 to 45 Hz.

2.2/

When an intentionally imposed moment was applied at 90° to the gauge axis and parallel to the mounting bolts, an error in calibration of ± 5% was observed. Care must be taken, therefore, to minimize the possibility of this happening in use.

2.3/

These transducers have been used by Harmon[1], to predict (to within ± 6%) the weights of vehicles passing over the Shawanaga Bridge.

2.4/

The transducer is also a usable static strain measuring device.

---

[1]A Study of Commercial Vehicles and their Multiple Presences, D.J. Harmon, University of Western Ontario, London, Ontario.

3/ DESIGN

The principle of design is the use of a strain-gauged steel bending element as the main source of electrical output from the transducer (see Figures 1 and 2). Electrical resistance gauges are bonded to the bending element by M bond AE 10 epoxy adhesive, and are wired to form a four-arm Wheatstone Bridge. The gauges used were manufactured by Micromeasurements of Romulus, Michigan, catalogue Number CEA-06-125 UW-350. The gauge factor was 2.09 ± 0.5% and the gauge resistance was 350Ω ± 0.3%. The gauges were arranged on the bending element such that gauges in adjacent arms of the Wheatstone Bridge encountered strains of opposite signs, and therefore gave sum outputs as shown in Figure 4.

When the demountable gauge is mounted on a steel test specimen, as shown in Figure 3, strain generated in the specimen between transducer mounting bolts is transferred to the transducer. The transducer is then deformed longitudinally, causing bending of the strain-gauged central beam. The resulting electrical output from the Wheatstone Bridge is directly proportional to the average specimen strain between the mounting bolts.

4/ MACHINED SHAPE

The transducer was machined from a 330 mm (13") x 51 mm (2") x 13 mm (1/2") mild steel bar. The small stand-off legs at the mounting holes effectively limit errors in gauge length to a maximum of 1 x the width of the leg, which is 3.175 mm (1/8"). The maximum error in gauge length would then be 0.97%. The stand-off legs are also useful in precluding contact with imperfections, such as paint build-up, weld spatter, and rust, in the bridge surface. The central beam, to which strain gauges were attached, was hand lapped after machining to give surfaces acceptable for the application of strain gauges. Figures 1, 2, and 3 illustrate the machined shape in detail.

5/ MOUNTING

Mounting of the transducer is accomplished by two 1/4" x 20 bolts at opposite ends of the transducer. After drilling two holes in the material upon which strain is to be measured (using a template with the precise hole centres predrilled), the holes may be tapped to accept the bolts. If drilling and tapping is not acceptable, the holes may be drilled to clear 6.35 mm (1/4"), and bolts of length sufficient to accept a 1/4" x 20 nut on the opposite face of the material may be used. A torque of 10 lb.ft may be used to place adequate holding pressure on the transducer to prevent slipping of the mounts. Any clamping system capable of applying the same holding pressure to the transducer mounting points may be used.

6/ TESTING

6.1/ Tensile Strain Test

To test the ability of the transducer to measure strain in tension, the transducer was mounted on a steel test specimen and placed in tension on a Tinius Olsen testing machine (see Figure 5). Opposite faces of the test specimen were strain-gauged using electrical resistance gauges from BLH Ltd., (catalogue Number FAE-50-12S6). These were 120Ω gauges ± 0.2%, with a gauge factor of 2.06 ± 1%. The gauges were placed on prepared surfaces immediately underlying the transducer, halfway between mounting holes. The test specimen was loaded incrementally and readings of specimen strain and strain output from the transducer were recorded at each increment of specimen strain.

Average specimen strain against strain output from the transducer is presented as a graph in Figure 6. Maximum deviations from a best line are also shown at selected points on the line to give an indication of maximum expected error in future use. Three cycles of this test were completed and all test data were plotted in Figure 6.

6.2/ Remounting Tests

The object of this test was to determine if any variation in slope of the best line, acquired from the tensile strain test, would occur due to variations in mounting, removal and remounting of the transducer. The test procedure was the same as for the tensile strain test with the exception that, between each cycle of loading, the transducer was removed from the test specimen and remounted. The test results were plotted, and are presented in Figure 7.

6.3/ Testing the Effect of Extraneous Moments

The object of this test was to determine the effect of an intentionally imposed moment at 90° to the transducer axis, and normal to the surface upon which the gauge was mounted. Moments such as this could be imposed

in use should the operator not use a proper drilling template and thus inadvertently place mounting holes at the wrong centres. As a result, the mounting bolts would apply an eccentric loading to the transducer at the mounting points.

The test procedure was the same as the tensile strain test except that during alternating cycles of loading, a moment was imposed at 90° to the transducer axis.

The moment was imposed by using a 'C' clamp to force the transducer centre down the maximum 2.38 mm (3/32") towards the face of the test specimen. After 'C' clamping, the tensile strain test was repeated. The results of the test are shown in graph form in Figure 8, with the difference in slope of the two lines, acquired from the data, being expressed as a maximum percentage of error.

6.4/ Temperature Stability Test

The object of this test was to determine the effectiveness of the temperature compensation of the four-arm Wheatstone Bridge applied to the transducer. The strain gauges used were small, working space on the bending element limited, and wiring difficult. This test was a quality control check.

After mounting the transducer on a steel test specimen, the assembly was placed in a cold chamber. Specimen temperature was monitored using a thermometer in contact with the specimen via temperature conducting grease. As the temperature of the chamber dropped, transducer output strain and temperature were recorded. The test data were plotted in Figure 9.

6.5/ Frequency Response

The dynamic characteristics of the demountable strain gauge were investigated by exciting the transducer with impacts, using a hammer, and analyzing the input and the output of the mechanical system of the transducer.

For the initial stage of the investigation, a transducer without strain gauges was used.

After suspending the transducer in space to isolate it mechanically from any other structure, it was excited with an instrumented hammer. The load cell used with the hammer was a Kistler, Model 922.

The response of the transducer was monitored by means of an accelerometer, B & K, Model 8307, placed at the location where the strain gauges were to be installed.

The results from the analysis of the excitation with the hammer, and the response of the accelerometer, indicated that the first natural frequency of the transducer in the free -- free condition was located at 135 Hz. The next two natural frequencies within the range of 2 kHz, were 400 Hz and 1700 Hz. The mechanical impedance of the transducer had the lowest value at 400 Hz.

During the next stage of the investigation into the dynamic characteristics of the demountable strain gauge, the output of the four-arm Wheatstone Bridge was monitored instead of the output of the accelerometer.

Analysis of the excitation, and the response of the transducer in the free -- free condition confirmed the results of the analysis of the initial stage of the investigation.

The dynamic behaviour under mounted condition was also investigated briefly. Theoretically, the response of the total vibrating system, the testing bar, and the transducer, will differ significantly from the response of only the transducer, in the free -- free condition.

The natural frequencies of the sub-system of the transducer will shift to higher values, because of the changed boundary conditions.

This behaviour was confirmed by the investigation of the transducer under mounted conditions, and no additional natural frequencies below 135 Hz were observed.

7/ DISCUSSION OF RESULTS

7.1/ Tensile Strain Test

The test results, as shown in Figure 6, indicated that the transducer output was linear and repeatable within ± 1.5%. This test became the method of calibration for future transducers of this type. Using other instrumentation, the output could well have been expressed in $\mu V/V/\mu\varepsilon$ as shown in Figure 6, as a calculated value from the recorded transducer strain output.

7.2/ Remounting Tests

The remounting test, as shown in Figure 7, indicates that the slope of the calibration curve does not change due to remounting the transducer. A zero shift can be expected, as seen by the series of parallel lines in Figure 7. It is expected that most conventional data logging and signal conditioning equipment should be capable of eliminating the effect of zero shifts due to remounting.

7.3/ Testing for the Effect of Extraneous Moments

Figure 8 indicates that the calibration of the transducer will be modified by imposing moments at 90° to the transducer axis and normal to the surface of measurement. Extreme care should be taken, therefore, to ensure that holes are drilled accurately, and that the surfaces of holding nuts are not irregular.

The moments applied during the test represented the maximum it was possible to apply, and resulted in deviation from the calibration factor of up to 5.1%.

7.4/ Temperature Stability Test

Temperature stability tests indicated that very little drift could be expected with change in temperature. The maximum recorded was 0.2 $\mu\varepsilon/°C$. If excessive temperature drift was encountered, the transducer was rejected for use.

7.5/ Frequency Response

The techniques that were used for the investigations into the dynamic characteristics of the demountable strain gauge did not allow for acquisition of a calibration over the frequency range of interest, due to a relatively high stiffness and a low output level of the transducer.

The information gained from this investigation shows that the first resonant condition of the transducer in the free -- free state is 135 Hz. By using an arbitrary factor of 3 to allow for the unknown damping ratio in the gauge, data obtained by using this transducer should be reliable up to approximately 45 Hz. It would be advisable, however, to obtain a calibration of the output of the transducer over the frequency range of interest before, or directly after, use.

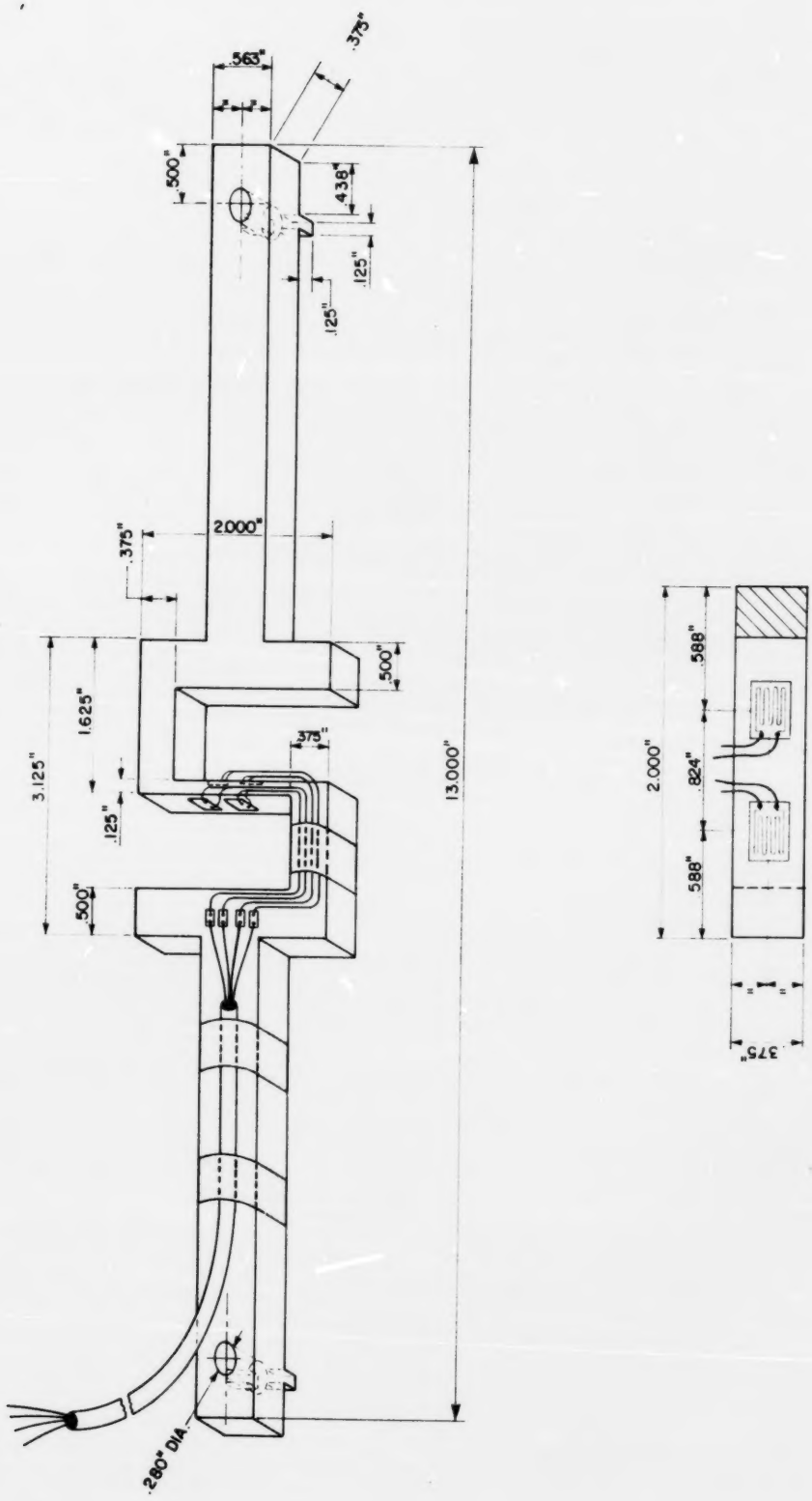


Figure 1/ Sketch of The Transducer

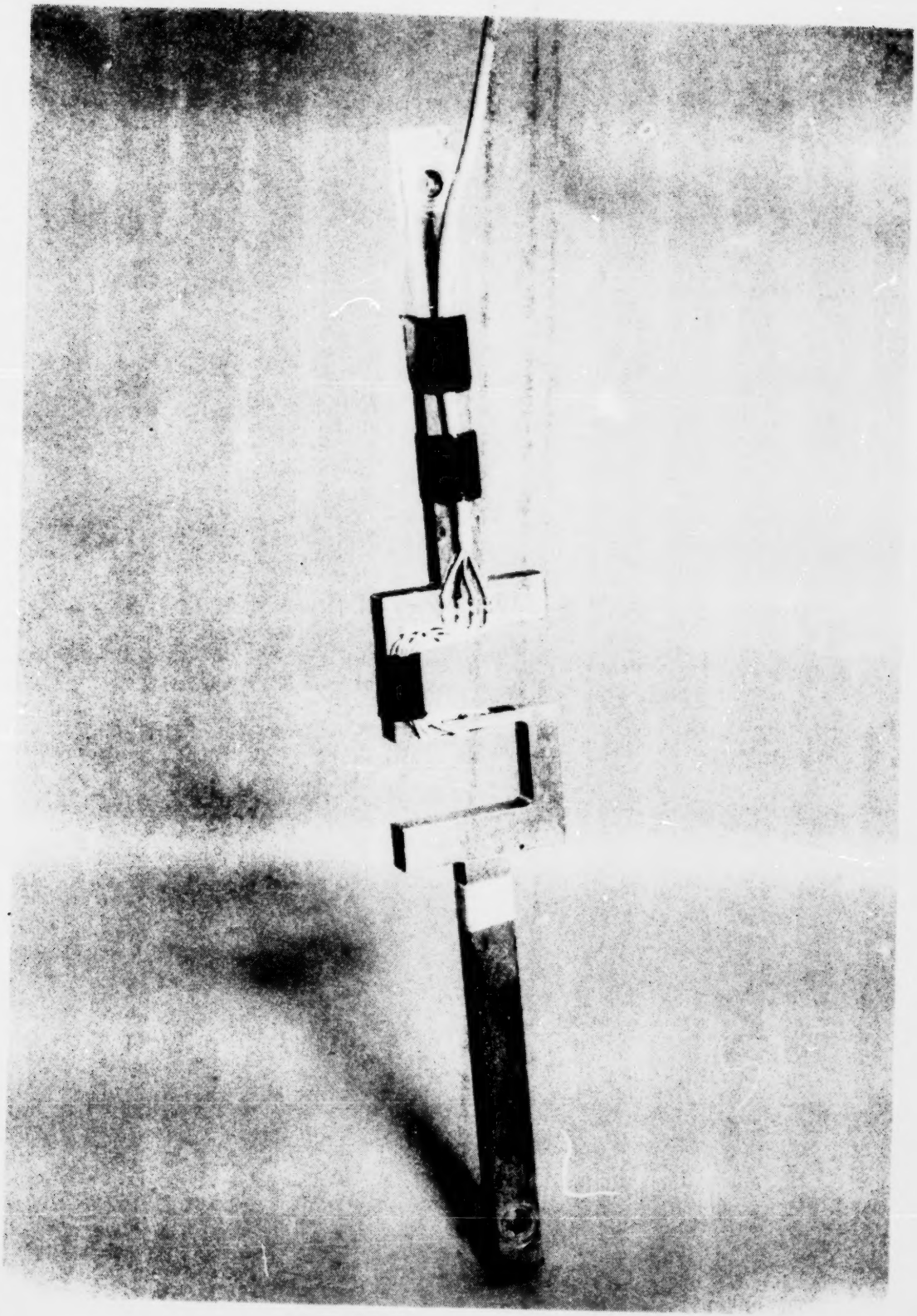


Figure 2/ Photograph of The Transducer

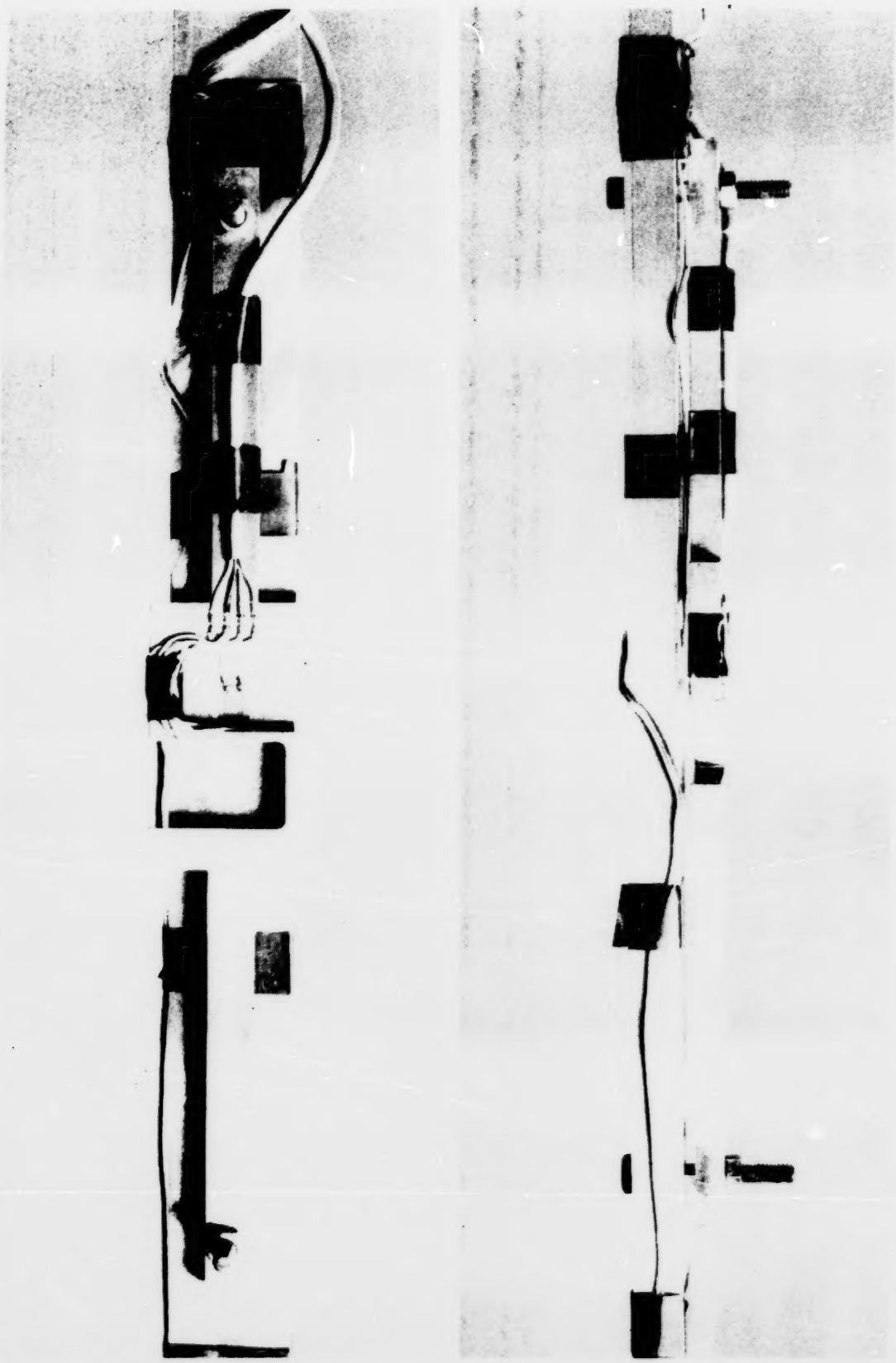
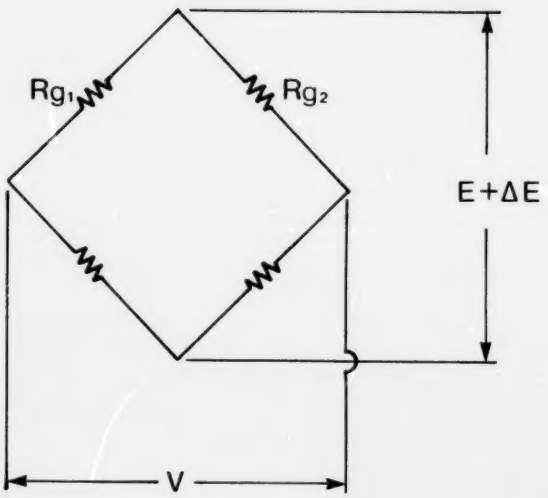


Figure 3/ The Transducer Mounted on a Steel Test Specimen



Assume: $Rg_1 = Rg_2 = Rg_3 = Rg_4$ and all are active strain gauges.

Then: $E = 0$ and :

$$\Delta E = \frac{V}{4}\left[\frac{\Delta Rg_1}{R_1} - \frac{\Delta Rg_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right]$$

since: $\varepsilon = \Delta R/R/G.F.$

where: ε is strain, and G.F. is the electrical resistance gauge factor, and:

$$K = \frac{V}{4} \times G.F.$$

then: $\Delta E = K[\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4]$, since the strain gauges are located on the transducer bending element such that:

$$\varepsilon_1 = -\varepsilon_2 = \varepsilon_3 = -\varepsilon_4$$

Then: $\Delta E = 4K\varepsilon_1$

FIGURE 4/ The Wheatstone Bridge Circuit

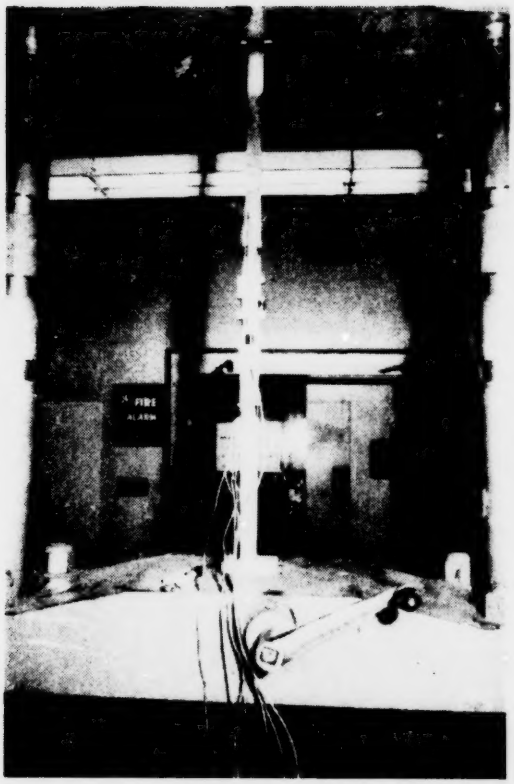


Figure 5/ Test Specimen Mounted in the Testing Machine

$$\text{SENSITIVITY} = \frac{\text{OUTPUT}}{\text{INPUT}} = 5.52\ \frac{\mu\epsilon}{\mu\epsilon} = 2.76\ \mu v/v/\mu\epsilon$$

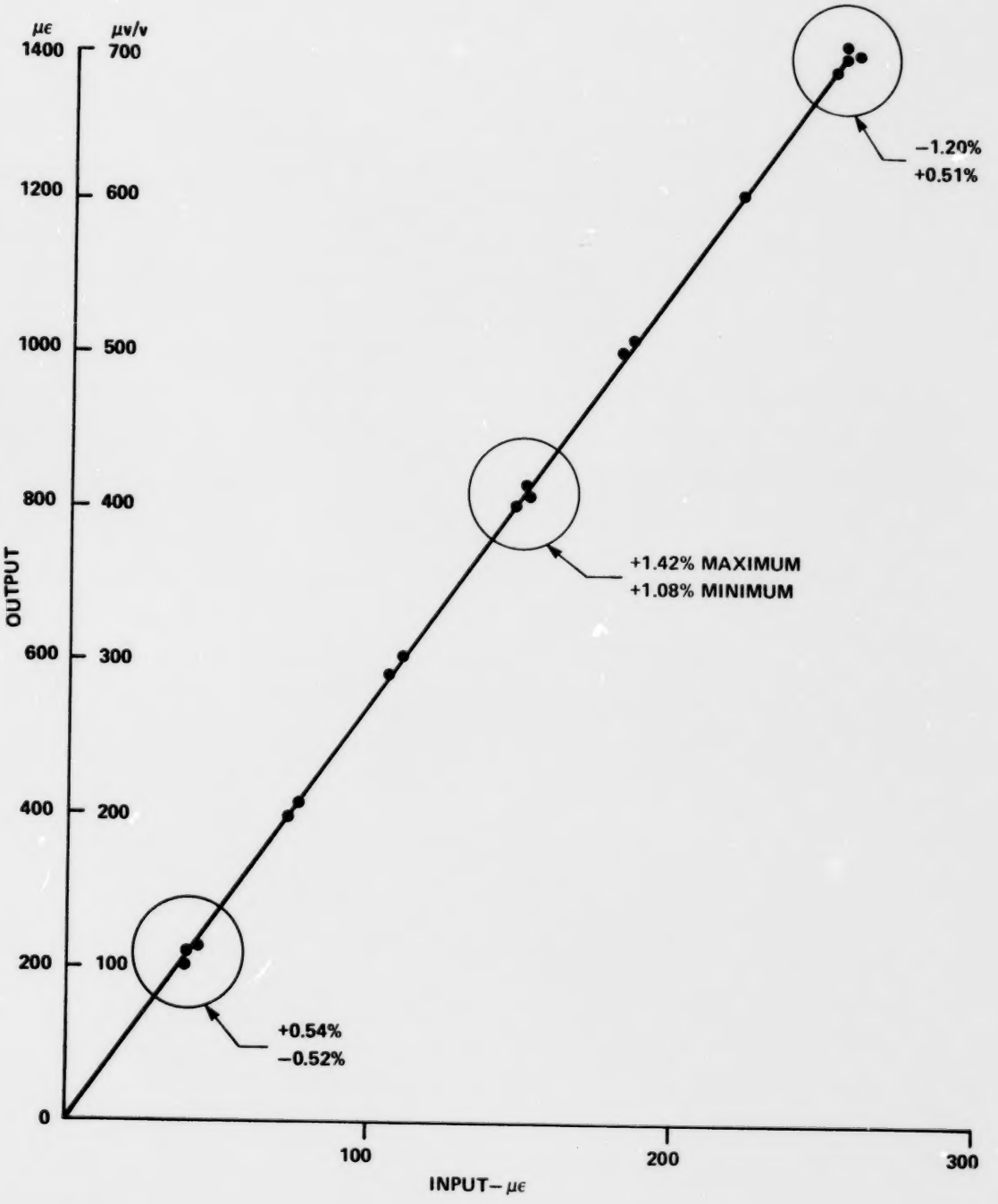


Figure 6/ Tensile Strain Test Results

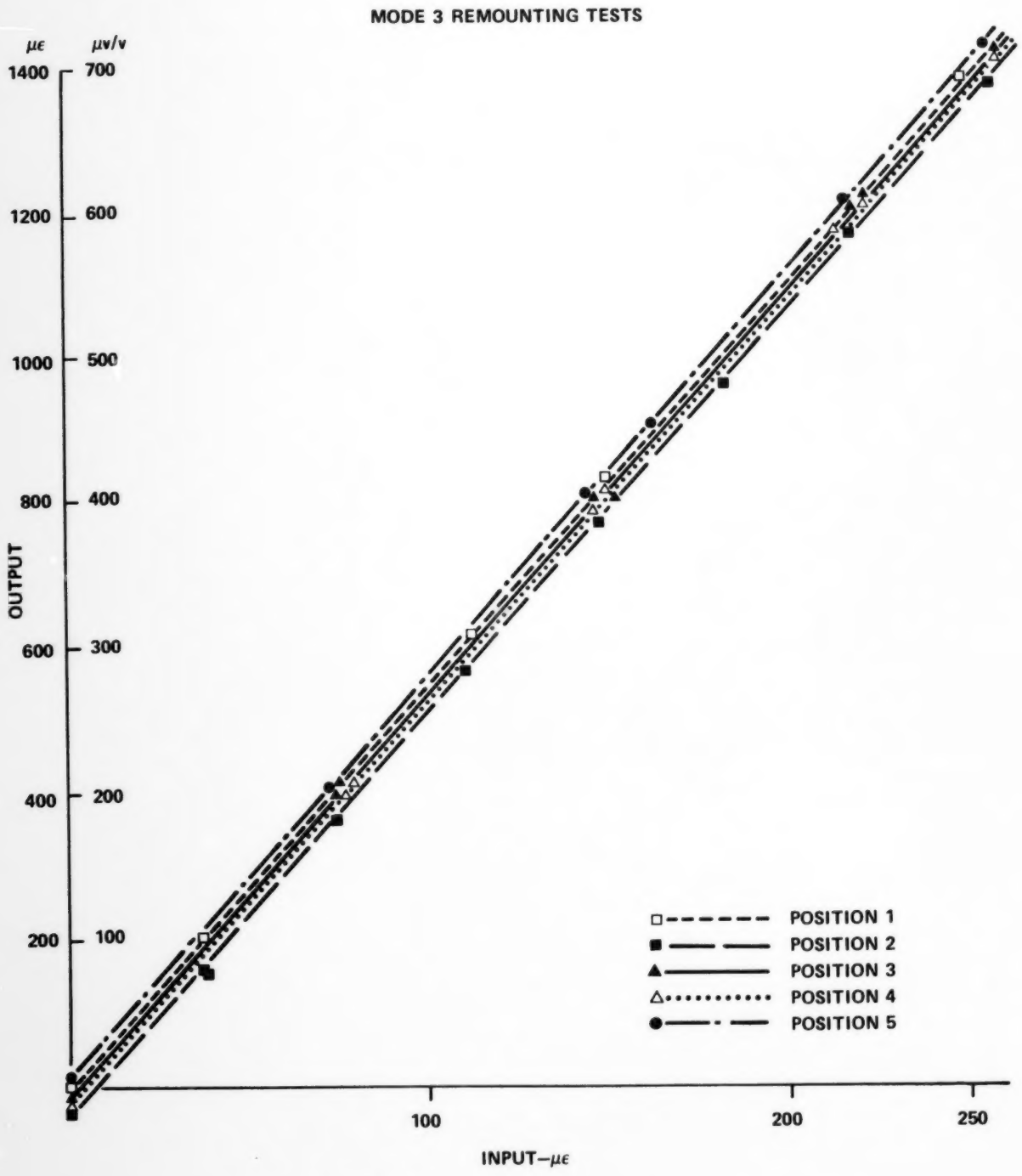


Figure 7/ Remounting Test Results

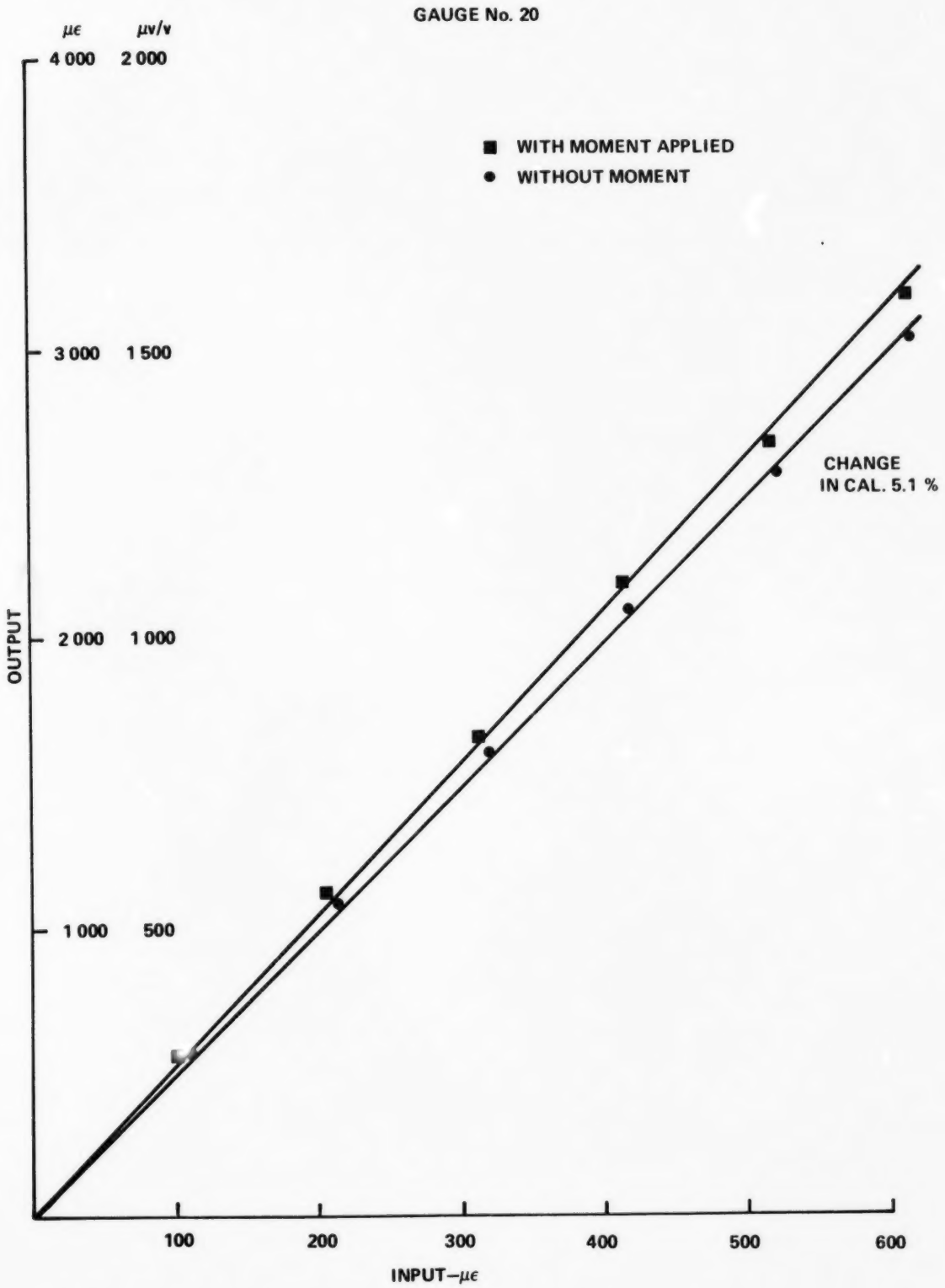


Figure 8/ Effect of Extraneous Moments Test Results

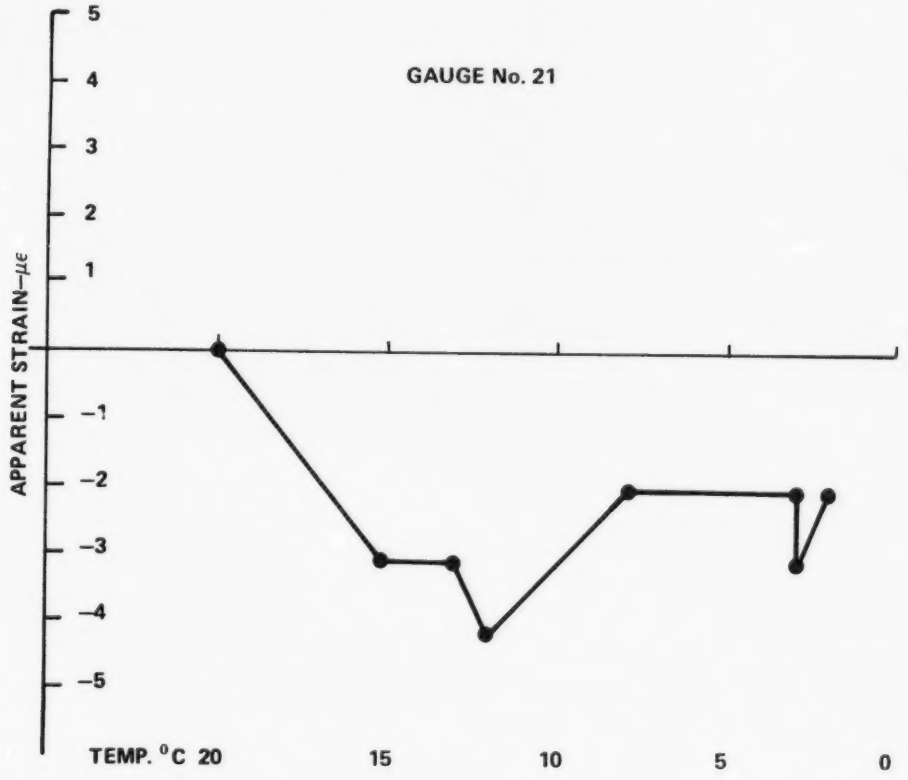
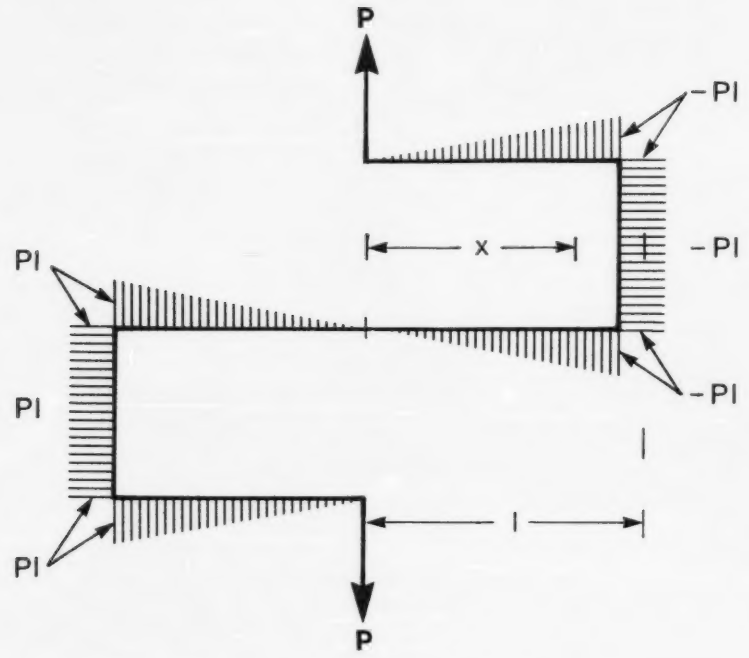


Figure 9/ Temperature Stability Test Results

APPENDIX A

Appendix A/ Structural Analysis



$$\ell = \frac{\text{beam length}}{2}$$

x = ℄ P to ℄ E.R. gauge

$$I = \frac{bd^3}{12} = \frac{0.360 \times 0.125^3}{12} = 5.85 \times 10^{-5} \text{ Moment of Inertia}$$

$$S = \frac{bd^2}{6} = \frac{0.360 \times .125^2}{6} = 9.38 \times 10^{-4} \text{ Section Modulus}$$

$$E = 30 \times 10^6$$

$$\text{deflection } \Delta = \frac{2Pl^3}{3EI}$$

Average Strain in underlying Materials causing the deflection =

$$\frac{\Delta}{\text{gauge length}} = \frac{\Delta}{12} = \text{Input}$$

$M_X = P_X$: that is the moment at one electrical resistance gauge site

Stress at the gauge site $\sigma = \frac{M_X}{S}$

and strain at the gauge site $\varepsilon_1 = \frac{\sigma}{E}$

therefore, the transducer output for any input strain may be expressed as $4\varepsilon_1$ since there are 4 active strain gauges in the Wheatstone bridge.